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NVO and the LSB Universe

James M. Schombert

Department of Physics, University of Oregon, Eugene

Abstract.
There is tremendous scientific potential in a National Virtual Observatory, particularly for projects that need to mine large databases for rare or unusual objects. However, the NVO will also make an impact on any project, large or small, the requires a mixture of datasets to explore a wide range of astrophysical phenomenon. In this article I discuss the influence of the NVO on research into the formation and evolution of low surface brightness (LSB) galaxies. In particular, I present the preliminary results from an NVO-style project that combines the DPOSS and 2MASS datasets to search for giant disk galaxies.

1. The Dataset Revolution

Astrophysical problems seem to increase in complexity with each successive generation. Observationally, new wavelengths and new flux limits bring about new phenomenon that demands more telescope time and begs theoretical interpretation. In the last 15 years we have seen an explosion in the amount, wavelength coverage and diversity of our datasets that have lead to numerous discoveries, but have also buried us in the sheer quantity of information.

Our community has also grown parallel to our data growth, but most of the high powered observational tools still lie in the possession of a few institutions. This disparity in big telescope resources has been offset, in a large part, by the formation of national data centers and the distribution of analysis software. Now an astronomer, regardless of the size of their home institution, can have access to high quality data and produce cutting edge science. With the addition of small grant programs (i.e. NASA's ADP program), an astronomical industry developed during the last two decades and discovery has moved from the hands of the few to the hands of the many. One only need to compare the impact of HST science on the astronomical community to that of Keck to see how the existence of non-proprietary datasets can push forward science.

As datasets have grow larger, there has been a strong emphasis on data mining and computational power. However, intelligent and cleverly designed projects depend more on access to direct tools rather then sophisticated algorithms. Thus, many astronomical projects today involve teams of scientists who bring together the diverse talents needed to attack the details of massive amounts of data. This is the goal of NVO, to provide the infrastructure and intellectual support for astronomical programs that compliment our already existing observational and theoretical foundations.

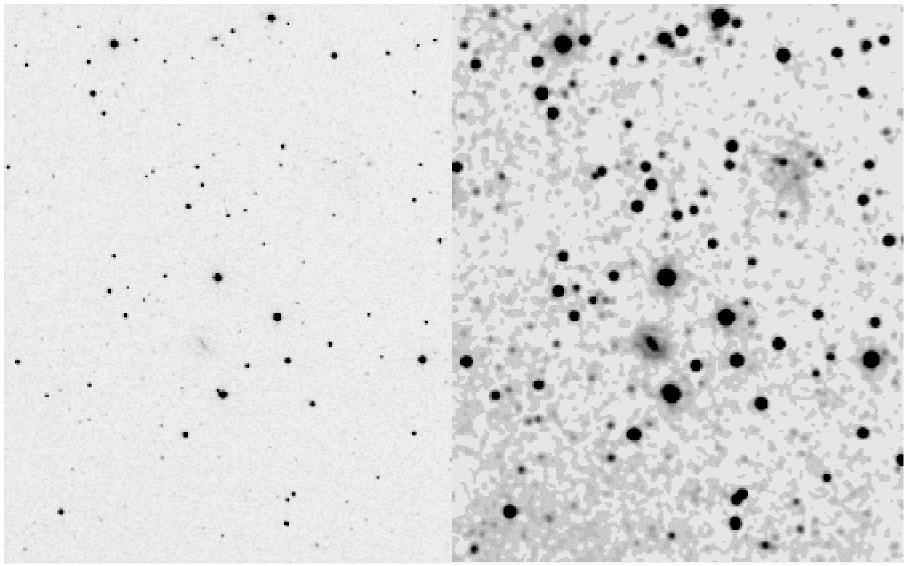

Figure 1. A subset of DPOSS normal (left panel) and smooth with a 5 pixel gaussian filter (right panel). A LSB disk galaxy is barely visible in the normal frame. A second LSB dwarf galaxy is discovered in the upper right-hand section of the smoothed frame. Both objects where detected in H I at Arecibo, the LSB disk has a velocity of 5,550 km/s, the dwarf is at 2,500 km/s.

Within the NVO concept there lies the goal of removing the division between the type of science and the type of data. Indeed, the greatest benefit the NVO may bring to us is to eliminate the specialization that divides our fields of research (stellar versus extragalactic) and between the wavelength regions (divided mostly due to the technology used to observe within the spectral regions of interest). As an example, one area of astronomy that could derive enormous benefit from the NVO is research into low surface brightness (LSB) galaxies.

2. LSB Universe

One area that is particularly challenging to the observational world is the universe of LSB objects. We can only study what we know to exist, and with respect to galaxies that means the object must reside in some catalog. While there has always been a push to find the faintest objects (meaning the lowest in mass as stellar luminosity maps into baryonic mass) or the most distant (meaning the closest to the galaxy formation epoch), it has only been recently that there has been much concern for objects with low luminosity density.

The LSB realm is interesting to many astrophysical problems. For example, star formation is normally a phenomenon associated with high gas density environments. Yet, LSB galaxies display many characteristics that indicates a history of recent star formation. Thus, studies into their past will probe star formation in new parameter space. The range of galaxy properties requires an examination of the LSB universe because galaxies at the extreme ends of the mass spectrum (dwarf and giant) tend to be LSB in nature. LSB galaxies also differ from their brighter cousins in that there gas masses often exceed their stellar masses. Thus, baryon counts of the Universe at high redshift will be underestimated without some knowledge of the distribution of LSB galaxies.

In some sense, the lack of pursuit of LSB research is technical in nature. To find the faintest, or most distant, galaxies becomes a simple process of building larger and larger collecting surfaces. However, achieving fainter levels of surface brightness to explore the LSB universe battles against the natural glow of the night sky and is not overcome with larger pieces of glass. Space imaging has the immediate advantage of getting above the sky glow, but the emphasis in space has been on small and faint, so pixel sizes to take advantage of high resolution images work against LSB objects by reducing the number of counts per pixel. Even in the non-optical portions of the spectrum the emphasis is always first on the detection threshold of point sources rather than design for sky brightness (see, for example, the 2MASS survey).

The first expeditions into the LSB universe where taken, of course, by Zwicky who hypothesized on the existence of 'hidden' galaxies as a counter to Hubble's notion that the galaxy luminosity function is gaussian in shape. By the 1960's, numerous galaxy catalogs by Arp, Sandage, van den Bergh (DDO) and de Vaucouleurs (RC2) had defined the Hubble classification system. These catalogs were primarily defined by HSB galaxies, but there were always appendices or notes concerning 'diffuse' objects, usually assumed to be nearby dwarfs.

Disney (1976) was the first to place the concept of galaxy visibility in an analytic form and to demonstrate that the mean central surface brightness of our galaxy catalogs was, in fact, a function of the natural sky brightness and not imposed by astrophysics. While the importance of this work is recognized today, galaxy evolution was a relatively new field at the time and the study of LSB galaxies remained in the background (no pun intended) until the mid-1980's.

3. LSB Detection

There was very little that the typical observational astronomer could do about the night sky problem until the mid-1980's with the evident of the Second Palomar Sky Survey. While the sky brightness had only degraded since the first Sky Survey, the finer emulsions and deeper plate material allowed for, at least, a cursory examination of the difference between the angular limited UGC and the new plate material. This resulted in the PSS-II LSB catalogs (Schombert & Bothun 1988, Schombert *et al.* 1992, Schombert *et al.* 1997) which were visual surveys, but demonstrated an increase of one mag arcsec^{-2} to the old catalogs. More importantly, it provided a jumpstart to the LSB field by simply providing a new list of objects in which to study.

The first visual surveys were extremely crude but spurred a more exacting search for LSB's using CCDs (O'Neil, Bothun & Cornell 1997, Dalcanton *et al.* 1997). Flattening is always a key parameter for LSB galaxy detection. Most CCDs on 1-meter class telescopes are sky limited in a few minutes of exposure time. The critical component in finding LSB galaxies, and measuring fluxes, is how well you know the sky value and how flat (on large and small scales) you can make your data. Transit CCD surveys offer the best method for sky flattening, since they allow the sky to pass through each pixel which is then summed for

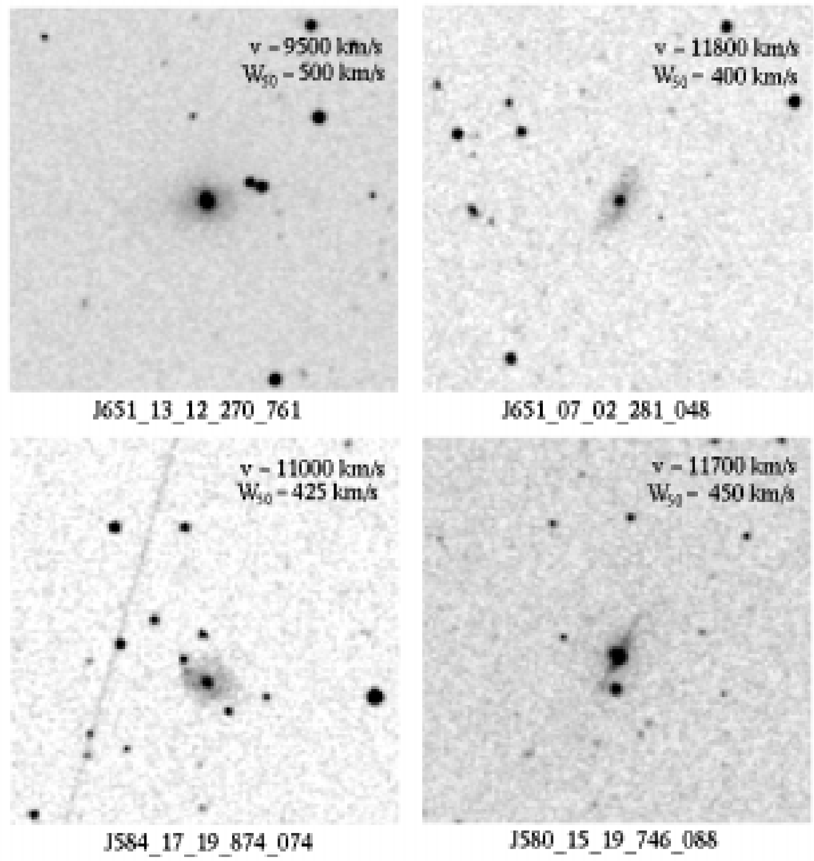

Figure 2. Four AGN Malin objects discovered from a combined search of DPOSS and 2MASS datasets. The near-IR 2MASS catalogs provide the low luminosity AGN sources (due to their anomalous colors) typical to the Malin class. The optical catalog is fast filtered for the presence of an LSB disk.

the entire scan. Long scans can suffer from temporal variations, but these can at least be quantified.

LSB detection is functionally a very difficult problem. The standard procedure is to detect all the HSB objects, mask them out, smooth and run the detection scheme again. Unfortunately, this will usually remove any LSB galaxies with bright bulges. They will be in the original catalog, but their LSB nature may not be known from whatever parameters are stored in the catalog.

One example of a smooth and search algorithm is shown in Figure 1. Here a sample of the sky from a J plate of DPOSS is shown in its raw form. A single LSB disk galaxy is obvious near the center of the frame. Smoothing with a gaussian filter enhances the detectable of the LSB disk and also discovers a second LSB galaxy in the top right portion of the scan. Both objects were detected in H I at Arecibo with velocities of 5,550 km/s and 2,500 km/s respectfully.

The smoothed image demonstrates the two major difficulties in automatizing LSB detection algorithms. The first is that the number of pixels distorted by stellar sources is extremely high at the surface brightness levels of interest. It is practically impossible to detect, in an automatic fashion, LSB objects near stars (although the human brain seems to carry out the task fairly well). Second, the uncorrelated background noise varys substantially over even this small piece of sky. This makes a systematic survey, to specific threshold levels, a technical challenge (what NASA would call completeness and reliability).

4. AGN Malin Search

One of the most intriguing classes of LSB galaxies is the supergiant disk systems, the Malin class. The prototype to this class, F568-6, was discovered from a visual search of the PSS-II (Bothun *et al.* 1990). While low in central surface brightness ($\mu_o = 23.4B$ mag arcsecs^{-2}), F568-6 is by no means low in luminosity ($M_B = -21.1$) nor low in total or H I mass. The Malin class contains the largest galaxies in the Universe, yet are notorious difficult to find and catalog (Sprayberry, Impey & Irwin 1996).

One of their properties provides a promising avenue for the cataloging of a significant number. Most Malin class galaxies have a weak AGN in their core. The current theory is that the copious gas supply in the disk provides the fuel for a central engine, even if at a low intensity (Schombert 1998). While the weak AGN appears as a point source, its near-IR colors would distinguish it from a stellar SED. Unfortunately, a survey of the sky in the near-IR will not, by itself, identify the Malin objects since the sky brightness at 2.2 μm is 2000 times higher than in the optical making their disk regions invisible. Thus, this project requires a 'virtual observatory', in this case the combination of two existing databases, DPOSS (optical) and 2MASS (near-IR).

The procedure is straight-forward, first isolate all the objects in the 2MASS catalog with non-thermal colors (i.e. outside some boundary defined by normal stars). Second, search the near-IR source positions on the blue plates of DPOSS with a fast area scan. A series of circular apertures are placed around the point source then tested against the local sky. LSB galaxy detection is effective if only a particular region is being tested against the background since varying diameters are checked which maximize the signal from the LSB disk versus the signal from sky.

A preliminary search was undertaken last winter using eight plates from DPOSS that contained some fraction of 2MASS coverage (about 3 square degrees). Forty candidates were produced of which ten of these objects were searched with the new, upgraded Arecibo telescope. The Gregorian system at Arecibo has a much wider velocity range, a critical element since the large Malin objects tend to be at velocities greater than 8,000 km/s. Eight of the ten candidates were detected at 21-cm.

Four of the detection's DPOSS images are shown in Figure 2. All have the characteristics AGN nucleus surrounded by a LSB disk. All eight also have H I widths in excess of 350 km/s (the typical spiral has a rotation width of 250 km/s). Assumingly these galaxies follow the baryonic TF relation (McGaugh *et al.* 2000), then their masses will exceed $10^{12} M_\odot$.

5. Conclusions

It is universally recognized that the NVO would be a powerful tool for the astronomical community. A particular emphasis will be placed on the need for the NVO to make the most efficient use of the large datasets in our present holdings and to future projects. However, perhaps one of the most common uses of the NVO will be of the one human/one workstation type project.

One such project I have described herein, the search for AGN Malin galaxies typifies my vision of how small projects will use the NVO. The merger of multi-wavelength datasets and simple tools, combined with a researchers experience in the astrophysical phenomenon, was used here to achieve a catalog of a new, and exciting, type of galaxy.

While each of our individual research interests may reap the benefits of the NVO, there is no doubt that the sum of the contributions of many small projects will also service to build the framework of the NVO. A system that we hope will be wavelength and research field independent.

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